VHE observations of unidentified EGRET sources

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Abstract. Observations of unidentified EGRET sources were made with the Whipple 10m imaging atmospheric Čerenkov telescope between Fall 1999 and Spring 2001. During this period, a high resolution 490 pixel camera with 4° field of view was present on the telescope. Characterization of the off-axis response of this instrument was done using observations of the Crab Nebula. No significant emission was detected from the eight unidentified EGRET sources observed and upper limits are presented as a function of position.

INTRODUCTION

Very High Energy (VHE) γ-ray astronomy is the term used to describe observations in the energy range from 300GeV to 100TeV. Ground-based instruments operating in this energy domain typically have large collecting areas, good angular resolution and relatively large fields of view. The atmospheric Čerenkov imaging technique is described in detail elsewhere [8].

Twenty five years of gamma ray observations in the MeV to GeV range, have produced nearly 300 cataloged sources. During its lifetime, the EGRET experiment aboard CGRO made the most significant contribution to the list of detected sources, although its relative insensitivity to the arrival direction of 100 MeV photons means that the location of many sources are only known to within $\sim 0.5°$. The majority of sources are, as yet, not firmly associated with objects at other wavelengths. In many cases the EGRET error circle is populated by a number of prospective X-ray, optical and radio sources which are all candidate associations.

OBSERVATIONS

Observations of eight unidentified EGRET sources, listed in Table 1, were made with the Whipple 10m imaging atmospheric Čerenkov telescope in Arizona USA. The instrument and its characteristics are described in Finley et al. [2].

For off-axis and extended sources the telescope is operated in ON-OFF mode. Each 28 minute scan of the source region is followed by a 28 minute control run offset from the source by 30 minutes in right ascension and in time. Taking the control data in this manner compensates for differences in brightness that are a function of elevation and azimuth.

TABLE 1. Unidentified EGRET sources selected for observation.

Source	Position RA	Dec	l	b	Observation dates	Exposure (min)
3EG J0423+1707	04:23:00	17:06:60	178.48	-22.14	2000/12 - 2001/02	248
GeV J0433+2907	04:33:38	29:05:56	170.50	-12.58	1999/11 - 2000/01	500
3EG J0450+1105	04:50:00	11:05:00	187.86	-20.62	2000/11 - 2001/01	274
3EG J0634+0521	06:33:12	05:53:07	206.18	-1.41	2000/11 - 2001/03	275
3EG J1323+2200	13:23:03	21:59:41	359.33	81.15	2001/01 - 2001/02	83
GeV J1907+0556*	19:07:41	05:57:14	40.08	-0.88	2000/05 - 2000/06	277
GeV J2020+3658†	20:20:43	36:58:38	75.29	0.24	1999/10 - 1999/11	139
3EG J2227+6122	22:27:14	61:22:15	106.53	3.18	2000/09 - 2000/10	341

* Roberts et al. [10] note that this source is over 1° away from 3EG J1903+0550, with which it is associated in Hartman et al. [3]. They conclude that this association is likely to be incorrect.

† This source is incorrectly associated with 3EG J2016+3657 in the third EGRET catalog. Roberts et al. [10] note that 3EG J2021+3716 is consistent with the GeV source.

ANALYSIS

Before any analysis is performed, all data are subject to a number of standard operations. First, the data is flat-fielded, a process which compensates for any non-uniformities in the camera. Second, artificially generated noise is added to each image to remove any biases that exist between the on-source and control observations, a process referred to as *software padding*. These biases result from the control data being taken while pointing to a different part of the sky which has different background light characteristics. Finally, each image is cleaned by ignoring all channels which do not have sufficient signal in them. The details of these procedures are described elsewhere [9, 1].

For extended sources or sources where the source location is not well determined, it is essential to reconstruct the arrival direction of the primary. The arrival direction must be inferred from the "shape" of the observed image. There are a number of methods available, the approach taken here, described in detail in Lessard et al. [7], is to assume that the arrival direction of the primary lies along the major axis of the shower image and is displaced from the center of the shower image by a distance given by,

$$disp = \xi \left(1 - \frac{width}{length}\right)$$

where $width$ and $length$ describe the shape of the recorded image and ξ is a scaling parameter.

This method yields two possible arrival directions, each of which is on the major axis of the shower image, seperated from the centroid by the calculated parameter, $disp$. When creating a 2D map the origin of each event is assigned to both possible directions in the hope that one will have an excess as more event origins are superimposed.

A sky map is then produced by building up a 2-dimensional histogram of the reconstructed arrival direction with respect to the center of the camera. Errors in reconstructing both the image axis and $disp$ are accounted for by convolving the final 2D map with a Gaussian function $g(\vec{r};r_0) = \exp(-r^2/2r_0^2)$, where r_0 is a scaling parameter chosen to maximise the significance of an excess.

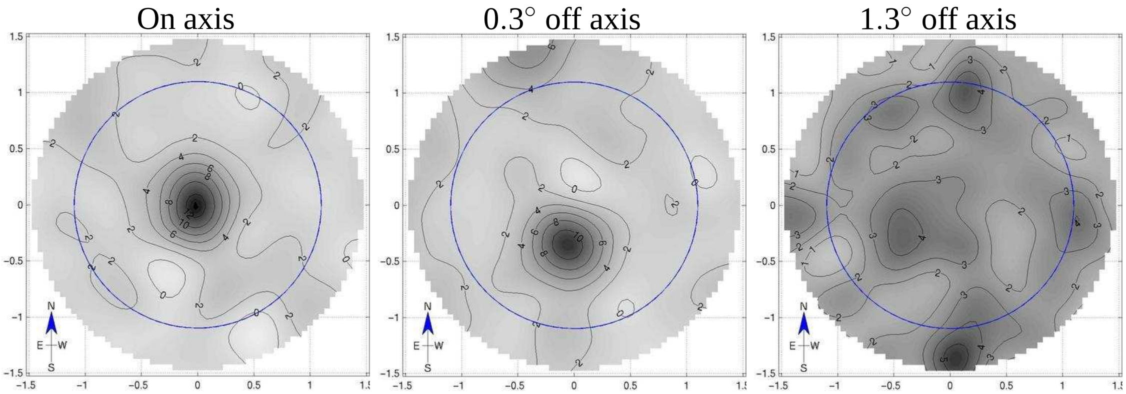

FIGURE 1. Observations of the Crab Nebula, offset by varying amounts from the center of the field of view. The contours show detection significance. Positions are in degrees from the center of the field of view with RA and Dec increasing toward the left and top respectively. A circle of radius 1.1° denotes the geometrical extent of the camera used. The observations at an offset of 1.3° place the Crab outside of this.

Calculation of excess signal, significance and upper-limit maps ($S(\vec{r})$, $\sigma(\vec{r})$ and $UL(\vec{r})$ respectively) is then done by convolving the ON and OFF counts with the smoothing function $g(\vec{r})$ in the appropriate manner, $S(\vec{r}) = \sum_{\vec{r'}} [ON(\vec{r'}) - OFF(\vec{r'})] g(\vec{r'} - \vec{r})$ and $\Delta S(\vec{r})^2 = \sum_{\vec{r'}} [ON(\vec{r'}) + OFF(\vec{r'})] g^2(\vec{r'} - \vec{r})$. Then $\sigma(\vec{r}) = S(\vec{r})/\Delta S(\vec{r})$ and $UL(\vec{r})$ is calculated from $S(\vec{r})$ and $\Delta S(\vec{r})$ by the method of Helene [4].

CALIBRATION

Calibration of the two dimensional analysis method was done using sets of observations of the Crab Nebula. Taking observations with the source location offset from the center of the field of view by various degrees and calculating the relative γ-ray rate allows a model of the detector response for off-axis and extended sources to be made.

Figure 1 shows significance maps for the Crab Nebula offset by three different amounts. In each of them the Crab is clearly visible. At an offset of 0.3° the γ-ray collection efficiency is 84% of what it is on axis. At an offset of 1.3°, with the source outside of the geometrical extent of the camera, the efficiency is 30%. The significance map for this data shows appreciable background contamination over the field due to the simple reconstruction approach of assigning the arrival direction of each photon to two points on the shower axis. More sophisticated approaches can reduce such false sources [7].

Figure 2 shows the relative collecting efficiency for offset sources. This curve is used to normalize detected emission rates or upper limits to the Crab flux.

RESULTS

In one case, GeV J1907+0556, the analysis indicated significant emission throughout the 7 square degree field, the result of large brightness differences between ON and OFF

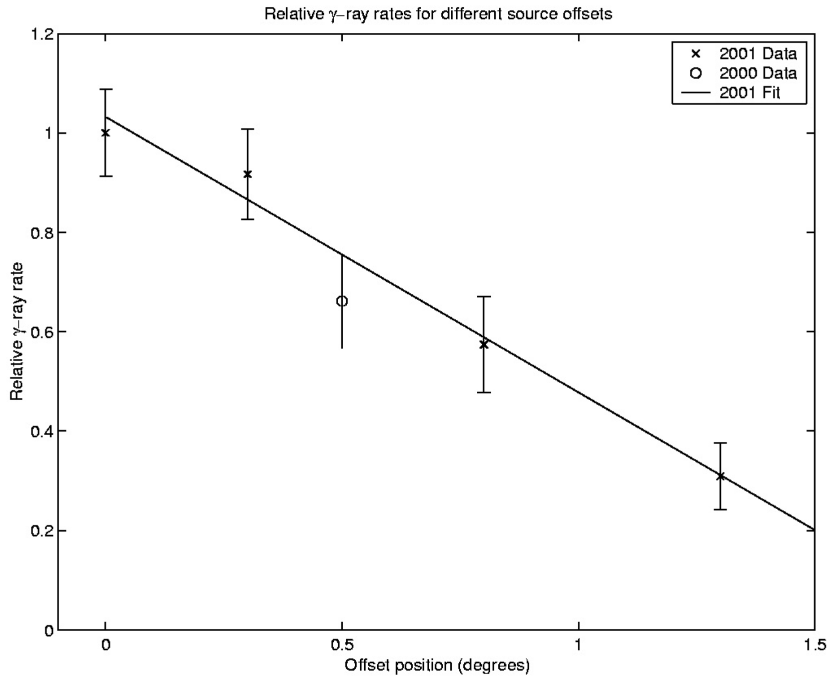

FIGURE 2. Relative Crab rate as a function of source offset. The off-axis response can be fit by a straight line.

TABLE 2. Upper limits derived from Figure 3.

Source	**Positional Error*** **(degrees)**	**Upper Limit †** **(E >430GeV)**
3EG J0423+1707	0.77	3.6
GeV J0433+2907	0.35	2.1
3EG J0450+1105	0.64	3.8
3EG J0634+0521	0.67	2.4
3EG J1323+2200	0.47	5.9
GeV J1907+0556	0.38	2.7
GeV J2020+3658	0.28	4.1
3EG J2227+6122	0.48	2.6

* 95% confidence circle from Lamb and Macomb [6] or Hartman et al. [3] as appropriate.

† Fluxes in units of $10^{-11}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ calculated from measured Crab flux of Hillas et al. [5].

observations that was not fully compensated for in padding. For this source alone, the ON source counts were scaled by a value calculated by examining the number of counts in the region of $1.4^\circ < r < 1.8^\circ$ from the center of the field of view.

No significant emission was detected from any source. Figure 3 shows upper limits on emission from the sources observed. Table 2 summarizes these results for the error circle of each object. In each case, the highest limit found in each region is quoted.

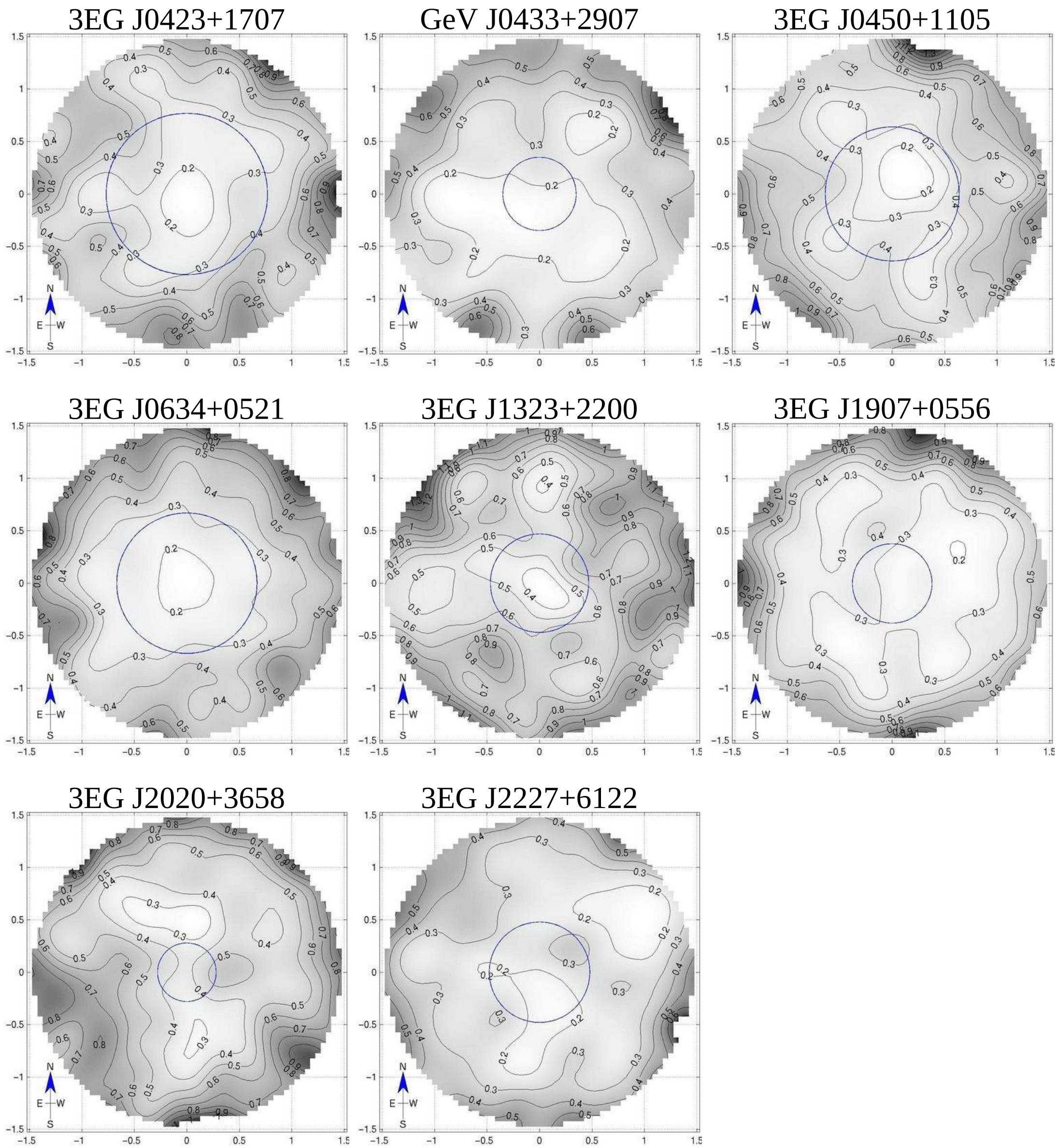

FIGURE 3. VHE upper limits on emission. Upper limits are given in units of the Crab Nebula flux. The axes are in degrees from the center of the field of view as given in Table 1. Increasing declination is toward the top of each plot, increasing RA to the left. The circle indicates the 95% confidence circle from Lamb and Macomb [6] or Hartman et al. [3] as appropriate. Where error ellipses have been given in in Lamb and Macomb [6], a circle with radius equal to the semi-major axis is displayed. The maximum upper limit in each 95% confidence region is given in Table 2.

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